TECHNICAL MEMORANDUMS
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No. 561

IMPROVING THE PERFORMANCE OF MULTI-ENGINED AIRPLANES BY MEANS OF IDLING PROPELLERS

THE "FREE-WHEEL" PROPELLER

By M. Pillard

From pamphlet issued by Ferran and Company, 1929

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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IMPROVING THE PERFORMANCE OF MULTI-ENGINED AIRPLANES BY MEANS OF IDLING PROPELLERS - THE "FREE-WHEEL" PROPELLER.*

By M. Pillard.

It is not considered necessary to dwell on the fact that the most important quality sought by increasing the number of engines of an aircraft is the safety resulting from the possibility of flying with one or more of them stopped.

This condition is the one attracting the most attention from constructors at present, because it limits the characteristics and carrying capacity and often definitely classifies an airplane as commercially useless.

All improvements of this nature affect, therefore, the characteristics of the whole airplane and may radically change its aerodynamic properties.

Among the various elements complicating the problem, there is one which is often not fully appreciated, but which nevertheless, is very important, namely, the braking effect due to the propeller of a stopped engine, the importance of which becomes very great with powerful engines involving the use of large propellers.

*"L'Amélioration des Avions Multimoteurs par l'Hélice.-L'Hélice Roue-Libre." Pamphlet published in 1929 by Ferran and Company, 42 Rue Longue-des-Capucins, Marseille, France.

In designing multi-engine airplanes, I have been impressed by the magnitude of this braking effect, and have been led to find a simple solution of this problem, which I have worked out in collaboration with Paulhan and Sensaud de Lavaud.

In order to demonstrate the importance of this device, I shall consider successively in what follows, the braking effect of the propeller of a stopped engine when the propeller is rigidly connected with the engine shaft and also when mounted on a free-wheel hub.

a) The case of a propeller of asymmetric section ordinarily employed.

b) The case of a propeller with a symmetric section.

I will then describe the mechanism of the free-wheel propeller as constructed by us and, in order to convince skeptics and verify the calculations, I shall give the results obtained in flight with this device mounted on a 1000 horsepower two-engine airplane.

Theoretical Study of "Receptive" Propellers

Although a few papers have already been written on "motive" aircraft propellers, very little systematic study has been made of "receptive" propellers. Mr. Leroux has recently published a paper on the latter type of propeller, but he confesses that lack of experimental results in this field of propeller performance prevents him from arriving at any definite conclusions.

Notwithstanding this lack of experimental data, I have not hesitated to employ Drzewiecki's analytical method which, for a propeller blade of constant width gives values sufficiently close to the experimental ones for use in practical and comparative calculations. The use of a propeller of any form doubtless gives results very close to those obtained with a constant-width propeller of the same power.

Determination of the Coefficients α, β, ρ
for two families of propellers,
for $\frac{H}{D}$ = 0.6; 0.7; 0.8; 0.9; 1.0

In order to determine these coefficients, we apply the fundamental formulas: ("Theorie generale de l'helice" by S. Drzewiecki, 1920, pp. 39 and 41)

$$P_m = \beta\, n^3\, D^5 = \frac{a\, V^5\, K_y\, Z}{\epsilon\,(2\pi)^2\, n^2}\,(I_2 + \mu\, I_3)$$

$$P_u = \kappa \times V = \alpha\, n^2\, D^4 \times V = \frac{a\, V^5\, K_y\, Z}{\epsilon\,(2\pi)^2\, n^2}\,(I_2 - \mu\, I_1),$$

from which, on assuming a blade width of $D/12$ and functioning near the ground, we obtain

$$\beta = \frac{C_z}{603}\left(\frac{V}{nD}\right)^4 (I_2 + \mu\, I_3)$$

$$\alpha = \frac{C_z}{603}\left(\frac{V}{nD}\right)^3 (I_2 - \mu\, I_1)$$

$$\rho = \frac{I_2 - \mu\, I_1}{I_2 + \mu\, I_3} \quad \text{with}$$

$$I_1 = \frac{\sqrt{1 + z^2}}{2} + \frac{1}{2} L \left(z + \sqrt{1 + z^2}\right)$$

$$I_2 = \frac{\sqrt{1 + z^2}}{3} (I + z^2)$$

$$I_3 = \frac{\sqrt{1 + z^2}}{4} \left(z^3 + \frac{z}{2}\right) - \frac{1}{8} L \left(z + \sqrt{1 + z^2}\right)$$

P_m = motive power in kg m/s

P_u = useful power in " "

β = power coefficient.

α = thrust coefficient.

ρ = propeller efficiency.

n = r. p. s.

D = propeller diameter.

a = number of blades.

V = velocity of air in front of propeller

$K_y = \frac{C_z \times d}{2g} = \frac{C_z}{16}$ near the ground

$\mu = \frac{C_x}{C_z}$

$z = \frac{\omega r}{V}$

$Z = \frac{\omega R}{V} = \frac{\pi}{\frac{V}{nD}}$

ϵ = reciprocal of relative width of blade $= \frac{R}{l} = \frac{D}{2l}$

We shall also assume that the values of C_z and of μ are the mean values measured on the mean profile of the blade located at 2/3 of the radius; that is, at the mean effective radius. This hypothesis evidently impairs the results, but only to an insignificant extent, especially in the region of small angles of attack - the region which interests us the most here.

Lastly, let us note that the pitch is always measured with respect to the line of zero lift of the blade profile, a fact which should always be remembered in comparing different results. Under these conditions we have determined the characteristic curves of two families of propellers, whose mean profiles and polars are given in Figures 1-4.

In order to facilitate the following calculations, we have also established the curves $k_\alpha = f\left(\frac{V}{nD}\right)$ and $k_\beta = f\left(\frac{V}{nD}\right)$, the coefficients k_α and k_β being, respectively,

$$k_\alpha = \frac{\alpha}{\left(\frac{V}{nD}\right)^2} \quad \text{and} \quad k_\beta = \frac{\beta}{\left(\frac{V}{nD}\right)^2} .$$

These families of curves having been thus plotted, it is easy to determine the "tractive resistance" of a propeller as soon as the "resisting couple" (torque) is known.

In fact, we may write

$$C\omega = \beta\ n^3\ D^5 = k_\beta \times \frac{V^2}{n^2\ D^2} \times n^3\ D^5 = k_\beta \times V^2\ nD^3$$

or

$$k_\beta = \frac{C \times 2\ \pi\ n}{V^2\ nD^3} = C \times \frac{2\ \pi}{V^2\ D^3} \ *$$

*Here C = torque, since $P_m = 2\ \pi\ n \times \text{torque} = C\omega$.

which enables us, knowing the torque, to determine the coefficient k_β and, from the family of curves, the corresponding value of k_α.

We may also write

$$\kappa\ (\text{traction}) = \alpha\, n^2\, D^4 = k_\alpha \frac{V^2}{n^2\, D^2} \times n^2\, D^4 = k_\alpha \times V^2\, D^2$$

which enables us to determine the value of the desired negative traction (Figs. 5-6).

General Formula for k_α

Let P_m denote horsepower absorbed by propeller at ground level;

c/C ratio of torque c to maximum motive couple C;

k_1 ratio $\dfrac{V/nD \text{ of adaptation}}{H/D}$ (generally = 0.75);

V_1 airplane speed with engine stopped;

V_a speed of adaptation;

n_a r.p.m. of engine at speed of adaptation;

β_a value of β for V/nD of adaptation.

Then

$$k_\beta = \frac{\beta}{\left(\frac{V}{nD}\right)^2} \quad \text{and} \quad k_\alpha = \frac{\alpha}{\left(\frac{V}{nD}\right)^2}$$

We have

$$k_\beta = c \times \frac{2\,\pi}{V_1{}^2\ D^3} = \frac{c}{C} \times \frac{75\ P_m}{2\,\pi\, n_a}{}^{*} \times \frac{2\,\pi}{V_1{}^2\ D^3} = 75\,\frac{c}{C} \times \frac{P_m}{n_a\, V_1{}^2\, D^3}$$

$$^{*}P_m \times 75 = \text{kg m/s}$$
$$= 2\,\pi\ n_a\ C$$
$$c = \frac{75\ P_M}{2\,\pi\, n_a}$$

and $\beta_a\, n_a^3\, D^5 = 75\, P_m;\quad D = \sqrt[5]{\frac{75\, P_m}{\beta_a\, n_a^3}};\quad D^3 = \frac{13.3\, P_m^{3/5}}{n_a^{9/5}\;\beta_a^{3/5}}$

$$k_\beta = 75\,\frac{c}{C} \times \frac{P_m \times n_a^{9/5}\;\beta_a^{3/5}}{n_a\, V_1^2 \times 13.3\, P_m^{3/5}} =$$

$$= \frac{75}{13.3} \times \frac{c}{C} \times P_m^{2/5} \times n_a^{4/5} \times \beta_a^{3/5} \times \frac{1}{V_1^2}$$

$$k_\beta = \frac{75}{13.3}\,\frac{c}{C} \times \beta_a^{2/5} \times n_a^{6/5}\, D^2 \times n_a^{4/5}\,\beta_a^{3/5}\,\frac{1}{V_1^2} = \frac{c}{C}\,\frac{\beta_a\, n_a^2\, D^2}{V_1^2}$$

and

$$\frac{V_a}{n_a\, D} = \frac{H}{D} \times k_1 \quad\text{and}\quad n_a^2\, D^2 = \frac{V_a^2}{\left(\frac{H}{D}\right)^2\, k_1^2}$$

whence

$$k_\beta = \frac{c}{C} \times \left(\frac{V_a}{V_1}\right)^2 \times \frac{\beta_a}{\left(\frac{H}{D}\right)^2} \times \frac{1}{k_1^2}$$

Since we can assume $k_1 = 0.75$

$$k_\beta = 1.77\,\frac{c}{C}\,\frac{V_a^2}{V_1^2}\,\frac{\beta_a}{\left(\frac{H}{D}\right)^2}$$

It is easy to show that, for the same airplane for which the ratio V_a/V_1 is very nearly constant, the value of k_β and, consequently, that of k_α depend only on c/C and H/D and, if a mean value of $\frac{V_a}{V_1} = \frac{1}{0.7}$ (for example) is assumed for all airplanes, we obtain the mean value

$$k_\alpha = 3.68\,\frac{c}{C}\,\frac{\beta_a}{\left(\frac{H}{D}\right)^2}$$

which enables us to determine the corresponding values of k_α and to plot the curves $k_\alpha = f\left(\frac{H}{D}\right)$ for the above families of propellers and for different values of c/C (Figs. 7-8).

According to these curves it is easy to show:

1) That for the same torque, the propeller with an asymmetric profile produces a braking effect considerably greater than that of a propeller with a symmetrical profile. For $c/C = 0.125$, the difference varies

from 40% for $H/D = 0.3$
to 22% " $H/D = 1.0$

2) That with an ordinary asymmetric profile, the propeller must be adjusted for a value of c/C near to 0.15. (less than 0.15 for low values of H/D and greater than 0.15 for large values of H/D).

This proof and the fact that on all existing airplanes, the propeller does not generally stop of itself, lead us to suppose that the torque of existing engines rarely exceeds 15% of the maximum torque, and not 20% as generally stated. (This should be verified for different types of engines, and would be worth clearing up.)

3) That the free-wheel propeller, namely, the propeller for which $\frac{c}{C} = 0$, always brakes much less than a propeller moving with the engine shaft, the symmetric-profile propeller being itself decidedly better than the propeller with an asymmetric profile.

Results of Laboratory Tests

In order to verify the above calculations, we have requested the Eiffel laboratory to determine for us, in their wind tunnel, the values of k_α for a family of propellers in their possession.

The family of propellers tested at the laboratory does not have blades of constant width. Consequently, the results cannot be absolutely superposed on those calculated above, but they can be brought close enough to use, since the results are but little affected by the shape of the blades. Moreover, these results differ from the calculated results by a constant quantity corresponding to the special braking effect of the hub and of the blade roots near the hub. By reducing this braking effect of the hub to that corresponding to a flat circular surface having a diameter equal to D/10, it is easily found that, in order to allow for the braking effect of the hub, all values of k_α must be increased by a constant quantity Δk_α, given by the expression

$$\Delta k_\alpha \times V^2 D^2 = \frac{\pi}{4}\left(\frac{D}{10}\right)^2 \times 0.08\ V^2$$

whence

$$\Delta k_\alpha = \frac{\pi}{4} \times \frac{0.08}{100} = 0.00063$$

On comparing the results thus computed, with those obtained in the laboratory, we obtain the curves of Figure 9.

On this graph we have also plotted the curve obtained in the laboratory with the propeller locked, so as to show the advantage of an idling propeller over a fixed one, that is to say, the uselessness of locking the propeller.

It is obvious that the calculated results and the experimental ones agree well enough to warrant their definite acceptance.

The Advantage of a Free-Wheel Propeller

In nearly all actual cases, the propeller, keyed to the engine shaft, continues to rotate with the latter in spite of the engine's being shut off. The gain obtainable with the free wheel must therefore be calculated with respect to the propeller in rotation with the engine, that is, with the corresponding torque.

This resisting torque is generally estimated at 20% of the maximum torque of the engine ($c/C = 0.20$) but, as already mentioned, we think this estimate is too high.

We will estimate this torque at 12.5% of the maximum engine torque, and we will only remark that the gains thus calculated are very discouraging.

Reduction in Head Resistance

Example 1.

Maximum speed of airplane	=	55 m/s = 198 km/h
Speed with engine stopped	=	38 " = 137 "
Diameter of two-bladed propeller	=	3.10 m
Engine power	=	500 hp
Maximum propeller speed	=	2000 r.p.m.
Relative pitch of propeller H/D	=	0.7
k_α for c/C = 0.125	=	0.0075
k_α with propeller locked	=	0.0050
k_α for c/C = 0	=	0.0020

Resistance eliminated by propeller revolving with engine:

$(0.0075 - 0.0020)\ 38^2 \times 3.1^2 = 76.50$ kg

Gain with propeller locked:

$(0.0050 - 0.0020)\ 38^2 \times 3.1^2 = 41.7$ kg

Example 2.

Maximum airplane speed		55 m/s = 198 km/h
Speed with engine stopped	=	38 " = 137 "
Diameter of two-bladed propeller	=	4.10 m
Engine power	=	500 hp
Maximum propeller speed	=	1000 r.p.m.
Relative pitch of propeller H/D	=	1.07

k_α for $c/C = 0.125$	=	.0042
k_α with propeller locked	=	.0045
k_α for $c/C = 0$	=	.0014

Resistance eliminated by propeller revolving with engine:

$$(0.0042 - 0.0014)\ 38^2 \times 4.1^2 = 70.5 \text{ kg}$$

Gain with propeller locked:

$$(0.0045 - 0.0014)\ 38^2 \times 4.1^2 = 78.0 \text{ kg}$$

Example 3.

Maximum airplane speed	=	50.7 m/s = 182 km/h
Speed with engine stopped	=	35.5 " = 128 "
Diameter of two-bladed propeller	=	2.25 m
Engine power	=	150 hp
Maximum propeller speed	=	2000 r.p.m.
Relative pitch of propeller H/D	=	0.9
k_α for $c/C = 0.125$	=	0.0050
k_α with propeller locked	=	0.00475
k_α for $c/C = 0$		0.0015

Resistance eliminated by propeller revolving with engine:

$$(0.005 - 0.0015)\ 35.5^2 \times 2.25^2 = 22.3 \text{ kg}$$

Gain with propeller locked:

$$(0.00475 - 0.0015)\ 35.5^2 \times 2.25^2 = 20.7 \text{ kg}$$

Gain in Useful Load and in Radius of Action

These reductions in the braking effect are very appreciable, but it is interesting also to examine the consequences of this improvement in the fineness of the airplane, that is, (for example), to determine the additional load that can be carried in flight.

Calling C_x/C_z the fineness with propeller locked and $\frac{C_x}{C_z} - \Delta \frac{C_x}{C_z}$ the fineness with a free-wheel propeller, the equations of flight are:

$$75 \rho P_m = \pi \frac{C_x}{C_z} V_1 \qquad (\pi = \text{load carried})$$

and $$75 \rho P_m = \pi' \left(\frac{C_x}{C_z} - \Delta \frac{C_x}{C_z}\right) V_1',$$

from which we derive

$$\pi' = \pi \frac{\frac{C_x}{C_z}}{\left(\frac{C_x}{C_z} - \frac{R}{\pi}\right)^{2/3}}$$

Example 1.- We can assume:

$$\pi = 6000 \text{ kg} \quad \text{and} \quad \frac{C_x}{C_z} = 0.111$$

whence $$\pi' = 6000 \left(\frac{0.111}{0.111 - \frac{76.5}{6000}}\right)^{2/3}$$

$$= 6000 \left(\frac{0.111}{0.0983}\right)^{2/3}$$

$$\pi' = 6000 \times 1.085 = 6510 \text{ kg},$$ or a gain in useful load

of $$\pi' - \pi = 510 \text{ kg},$$

representing, in fuel saved, an addition of 660 km (410 miles) to the radius of action (for a two-engine airplane with one engine stopped).

Example 2.- The additional load for the second case, determined in the same fashion, would be

$$\pi' = 6000 \times 1.08 = 6480 \text{ kg}, \quad \text{or a gain}$$

of

$$\pi' - \pi = 480 \text{ kg},$$

representing, in fuel saved, a supplementary radius of action of 621 km (for a two-engine airplane with one engine stopped).

Example 3.- This example is based on the assumption of 1800 kg load.

$$\pi' = 1800 \left(\frac{0.111}{0.111 - 0.0124}\right)^{2/3} = 1800 \times 1.08$$

$$= 1940 \text{ kg},$$

$\pi' - \pi = 140$ kg, representing an additional radius of action of 625 km (for a two-engine airplane with one engine stopped).

This represents a gain, due simply to the use of the free-wheel propeller, of one kilogram raised or 1300 meters radius of action per horsepower of the stopped engine.

Practical Construction of the Free-Wheel Propeller

The preceding calculations are intended to show what can be expected from the use of a free-wheel propeller. We will now consider briefly how such a device can be made.

The following description relates to one method of making such a device. It may be possible to find ways for improving this device still further. It is interesting to note, however, that the first one made has already proved very satisfactory. It weighs only 10 to 12 kilograms additional for 500 hp at 1000 r.p.m., and 7 to 8 kg for the same power at 2000 r.p.m.

This device for releasing the propeller when the engine stops consists of interposing, between the engine shaft and the propeller, a so-called "free wheel" which enables the transmission of force in only one direction, namely, from engine to propeller and not in the opposite direction, that is, from propeller to engine.

The free wheel can be interposed between the crank shaft and the propeller hub, or even in the reduction gear (if the engine has one). We prefer the solution involving the interposition of a free wheel between the engine shaft and the propeller hub, thus forming a free-wheel hub which can be mounted on the end of the engine shaft like an ordinary hub.

The sectional drawing and photographs show the construction of the free-wheel hub with sufficient clearness.*

*For a detailed description of this mechanism as applied to an automobile, see "The de Lavaud Automatic Transmission" in S.A.E. Journal, Vol. XXIII, pp.571-582, December, 1928.

The Sensaud de Lavaud free wheel is of the jamming type, that is to say, it produces a shockless drive, the play involved being only a few hundredths of a millimeter. When the engine is running, the rollers are jammed between the driving disk and the crown wheel and all the parts move together and the transmission takes place normally.

When the engine is stopped and the air current continues to turn the propeller, the rollers are automatically released and the propeller turns by itself as a windmill.

If, after flying with an engine stopped, the engine is started again, it re-engages the rollers as soon as the speed of the engine exceeds that of the propeller.

During the tests we observed that this device did not interfere in any way with the proper functioning of the engine. The only disadvantage is the impossibility of starting the engine on the ground by means of a cartridge starter. This disadvantage is eliminated by employing a starter of the auxiliary compression type. In flight, since the freely revolving propeller offers no resistance, the engine starts much easier.

Test Results

In closing this description, it is interesting to know the results of tests conducted on the ground and above all in flight, inasmuch as they confirm our predictions in all points and consequently corroborate our method of reasoning.

Statically, the free-wheel hub has successfully undergone the prescribed 30-hour tests with sudden starts, frequent variations of engine torque, etc., without any sign of wear or any disturbance in functioning.

A flight test was made July 10, 1929, on a "Farman 180" airplane, the "Oiseau Bleu" (Bluebird), a tandem two-engine airplane of 1000 hp (two 500 hp Farman engines) at 1000 r.p.m. The weight at the time of the tests was 6000 kg (13,228 lb.).

1) With the rear propeller mounted on a free-wheel hub, the airplane climbed to 1250 m (4100 ft.) with both engines running. After shutting off the rear engine it was able to maintain this altitude indefinitely. Then, after descending to 800 m (2625 ft.), it climbed again with only one engine running, as shown on the accompanying photograph of the barogram (Fig. 13).

2) With the same propeller mounted on an ordinary hub, the airplane climbed with the same load to the same altitude of 1250 meters. One engine was then stopped, and the airplane began a descent, which the pilot stopped after 7 minutes and 40 seconds, considering the test conclusive (Fig. 14).

The propeller used in these tests was a Chauviere two-bladed propeller No. 89169, diameter 3.5 m (11.5 ft.), with broad blades. During the two tests the front engine was kept at 2100 r.p.m., the air speed being 115 km/h (71.5 mi./hr.) in both cases. With the propeller fixed, the rear engine made 900 r.p.m. (the propeller, 450 r.p.m.). The speed of the free-wheel propeller could not be measured, but was estimated by the pilot and mechanic at about 600 r.p.m.

The two barograms show a difference in the climbing speed of at least 0.4 m/s between the two tests, which corresponds to an additional load carried with the free-wheel propeller of over 500 kg (1100 lb.), that is to say, an increase in the radius of action, with only one engine running, of more than 650 km (about 400 mi.).

Lastly, it was observed that the tail surfaces, which vibrated strongly with the fixed propeller, did not vibrate at all with the free-wheel propeller.

Conclusions

The free-wheel propeller increases the radius of action of two-engine airplanes by 600 to 650 km (373-404 mi.) with one engine stopped. The gain is of the order of 400 to 500 km (about 250-310 mi.) for a three-engine airplane, and of 650 to 700 km (404-435 mi.) for tandem two-engine airplanes with the rear engine stopped. The device weighs 8 kg (17.6 lb.) for a 500 hp engine with direct drive, and 12 kg (26.5 lb.) for a 500 hp engine with reduction gear.

Translation by
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for Aeronautics.

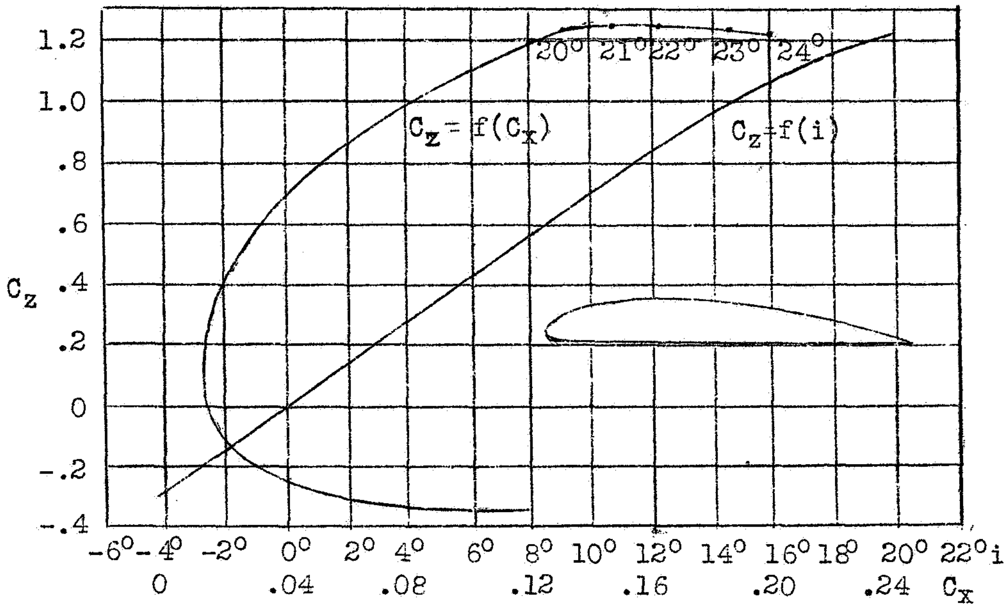

Fig.1 Polar of profile I.(Angle of attack measured from zero lift position.)

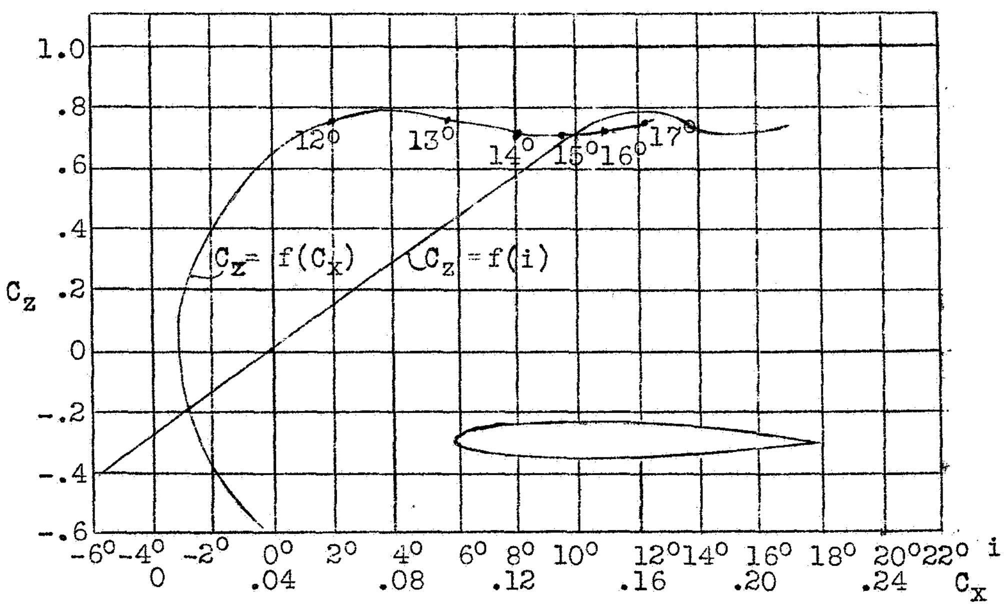

Fig.2 Polar of profile II. (Angle of attack measured from zero lift postion.)

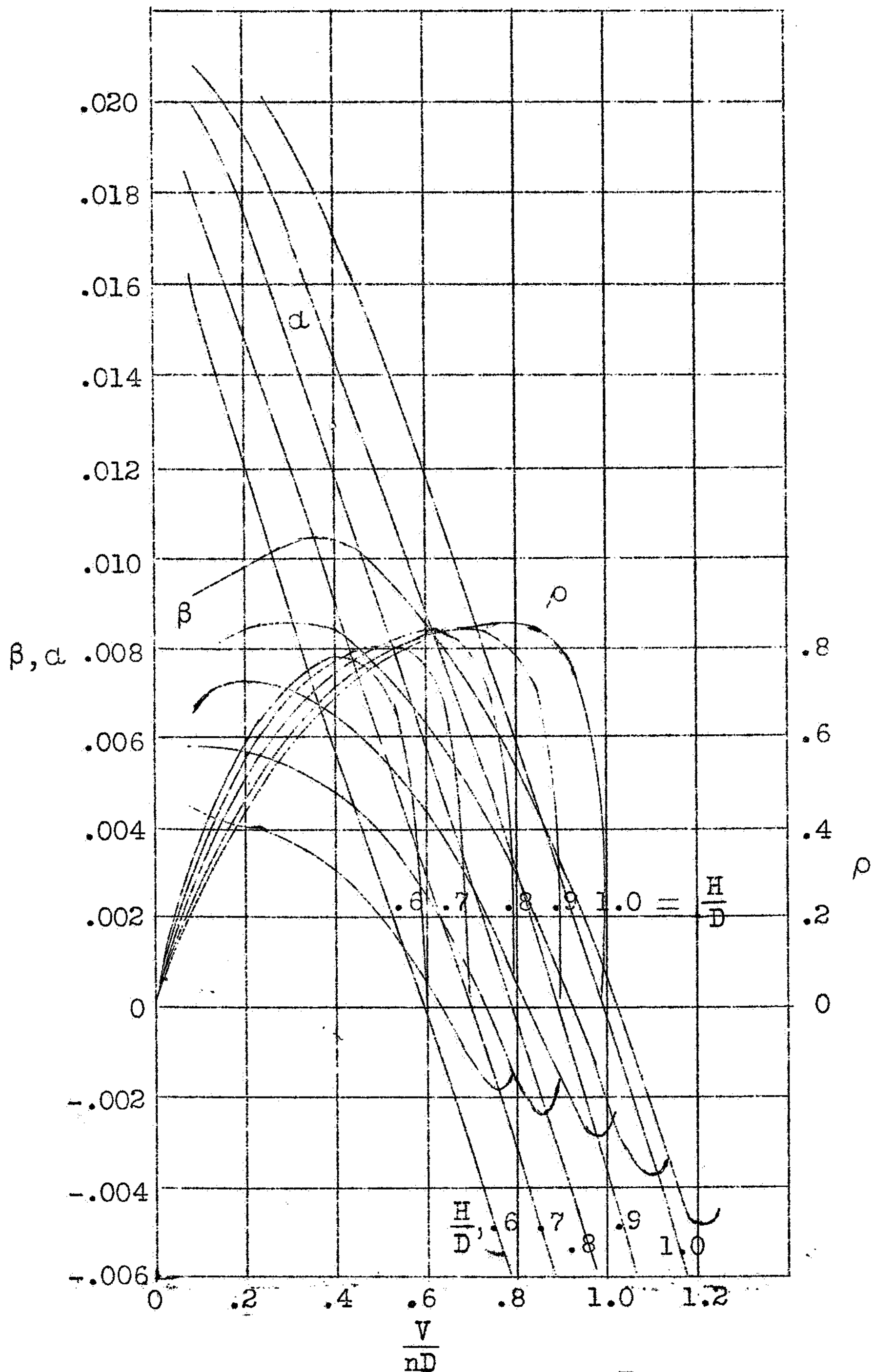

Fig.3 Characteristic curves, β, α, ρ = f($\frac{V}{nD}$) for a family of propellers with profile I. l, constant = $\frac{D}{12}$; 2 blades.

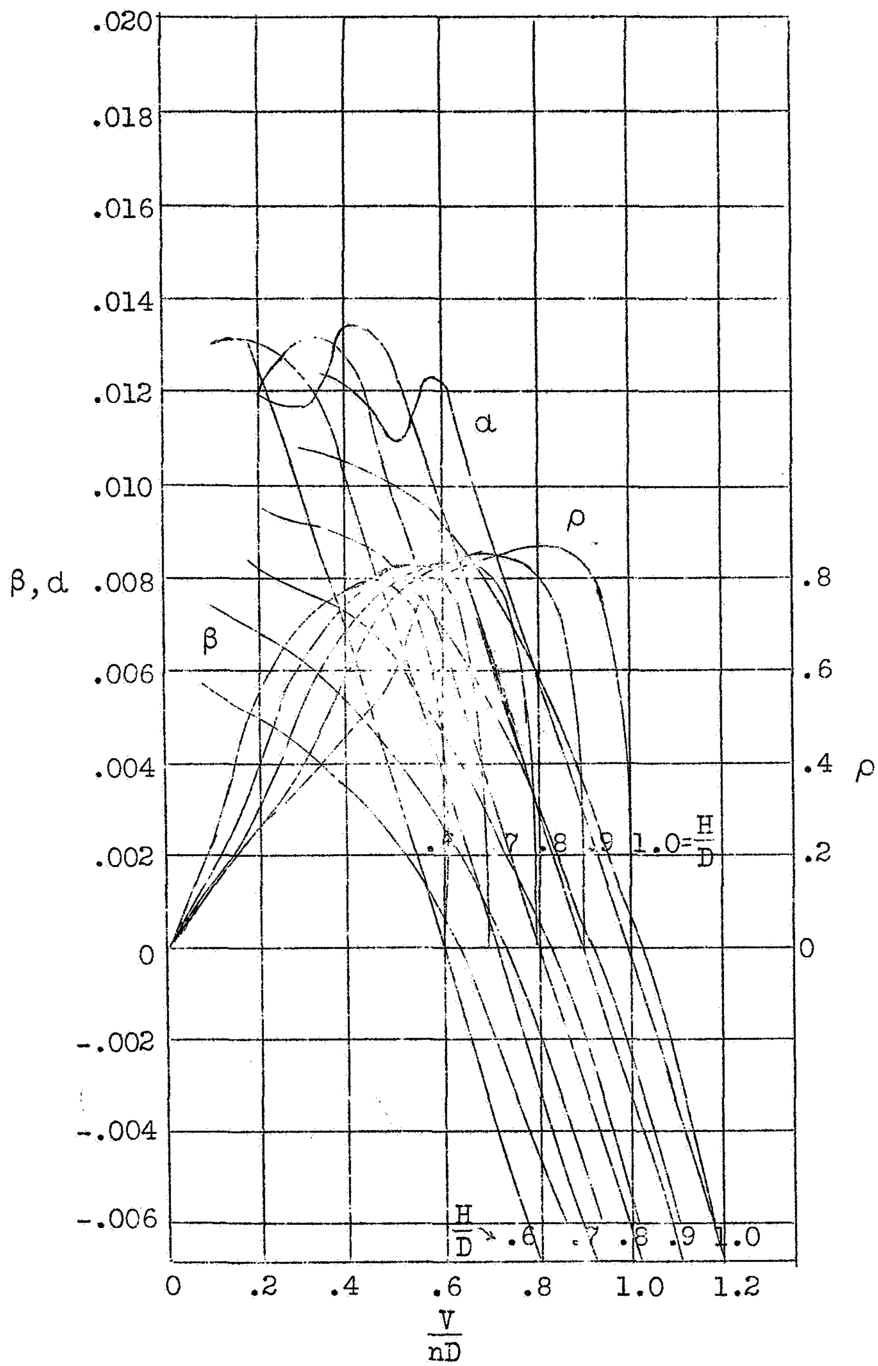

Fig.4 Characteristic curves, $\beta, \alpha, \rho = f\left(\frac{V}{nD}\right)$, for a family of propellers with profile II. L, constant $= \frac{D}{12}$; 2 blades.

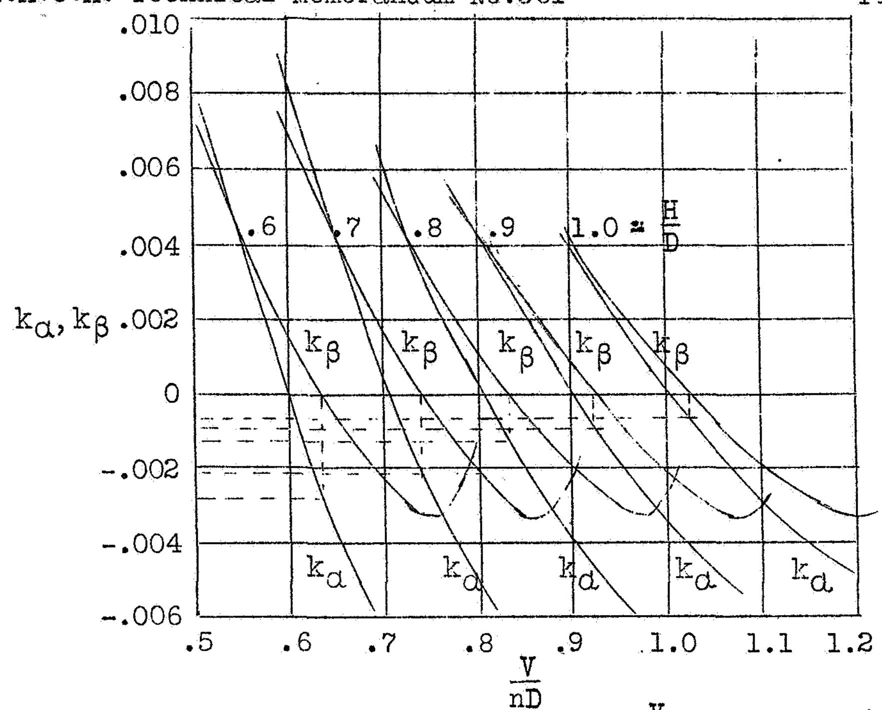

Fig.5 Characteristic curves, k_α, $k_\beta = f(\frac{V}{nD})$, for a family of propellers with profile I. l, constant $= \frac{D}{12}$; 2 blades.

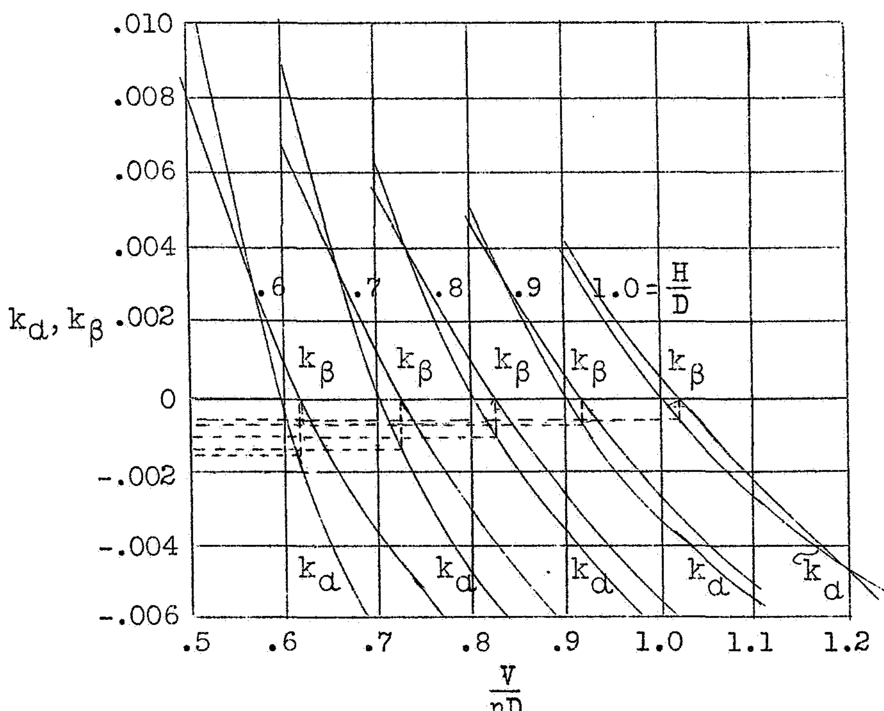

Fig.6 Characteristic curves, k_α, $k_\beta = f(\frac{V}{nD})$, for a family of propellers with profile II. l, constant $= \frac{D}{12}$; 2 blades.

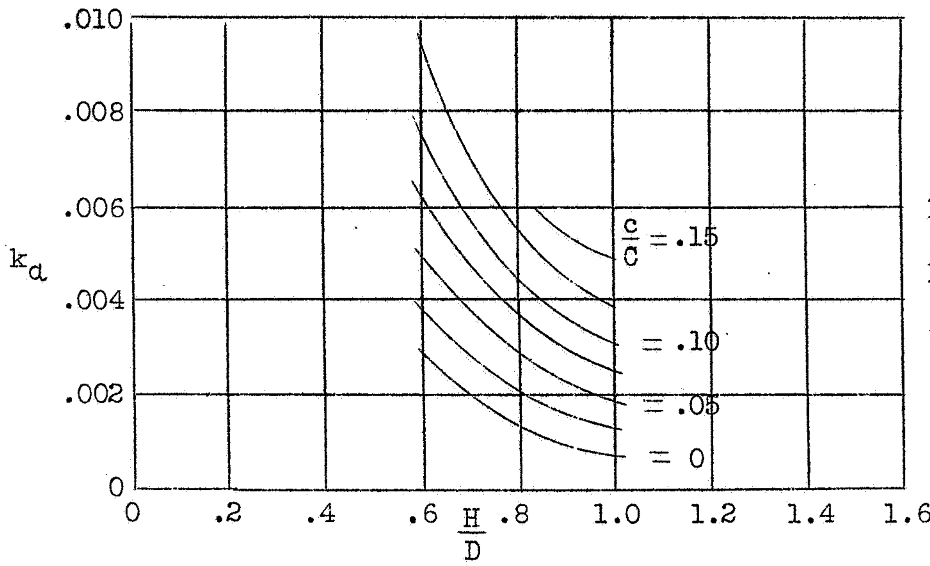

Fig.7 Braking coefficient $k_d = f(H/D)$. l, constant = D/12; 2 blades. Profile I

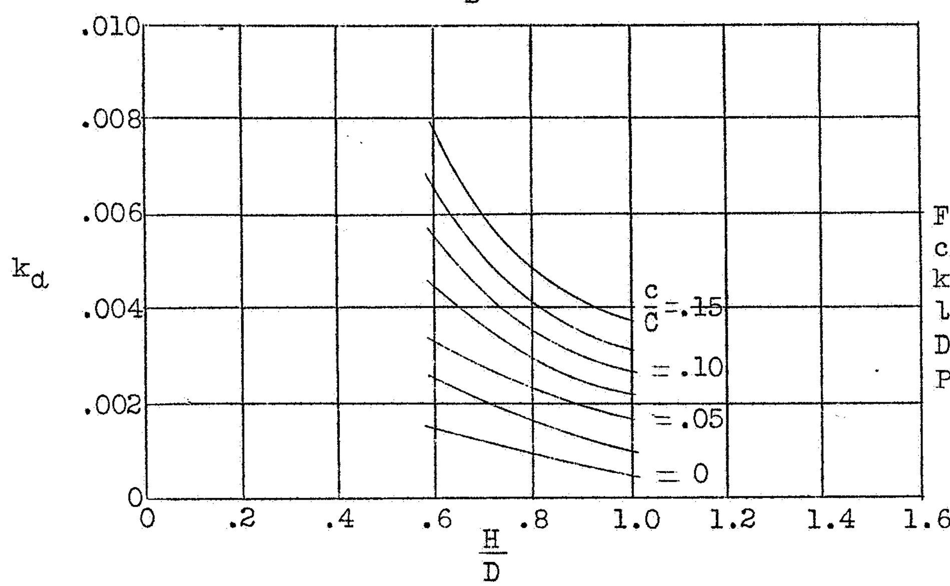

Fig.8 Braking coefficient $k_d = f(H/D)$. l, constant = D/12; 2 blades. Profile II

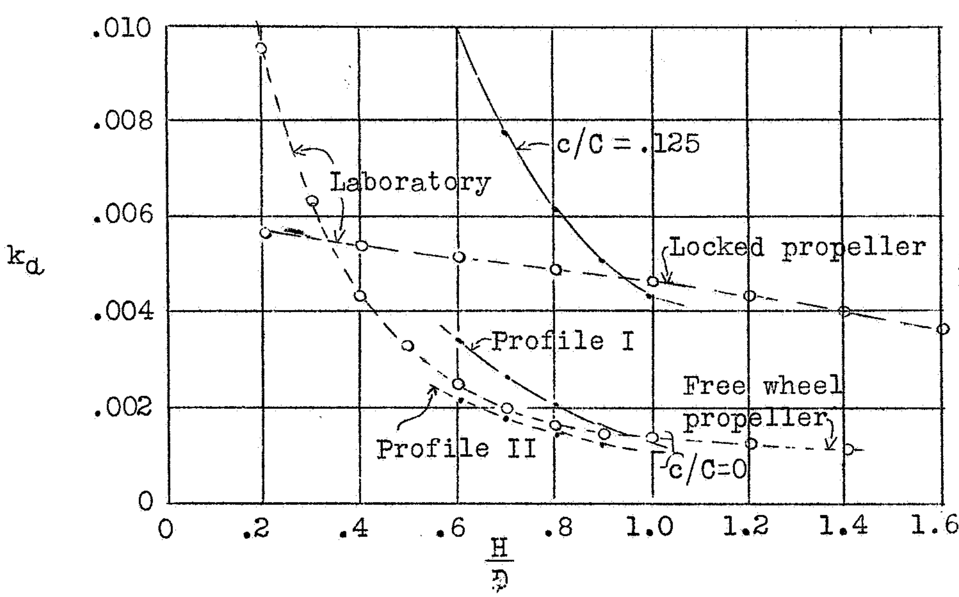

Fig.9 $k_d = f(H/D)$

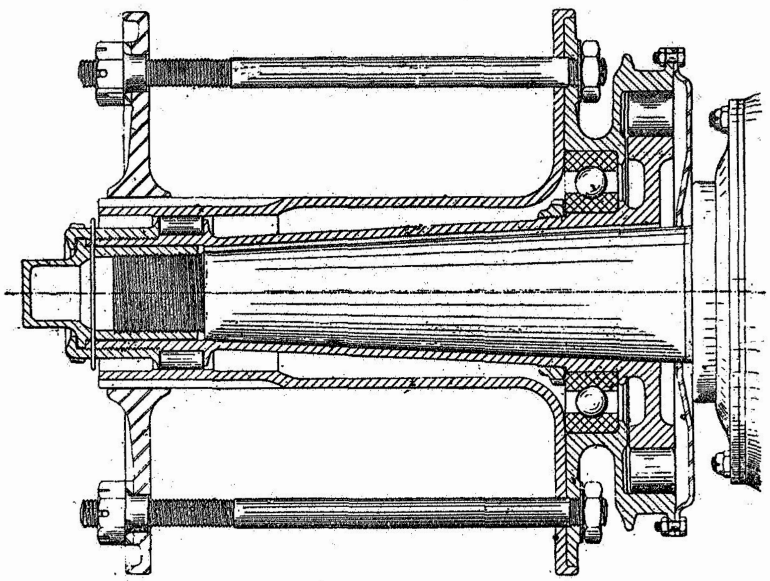

Fig.10 Longitudinal section of a free-wheel hub for a wood propeller, 500 hp 1000 r.p.m.

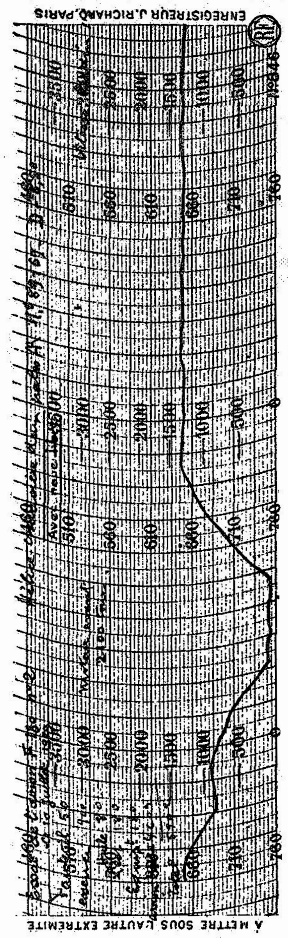

Fig.13 Record of flight with rear propeller equipped with free-wheel hub. Front engine running at 2100 r.p.m.

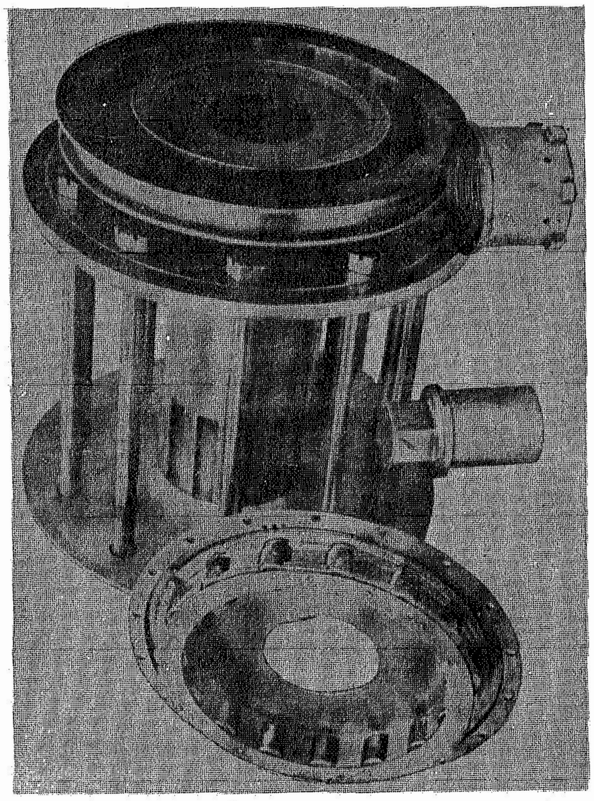

Fig.11 Free-wheel hub for wood propeller with free-wheel removed

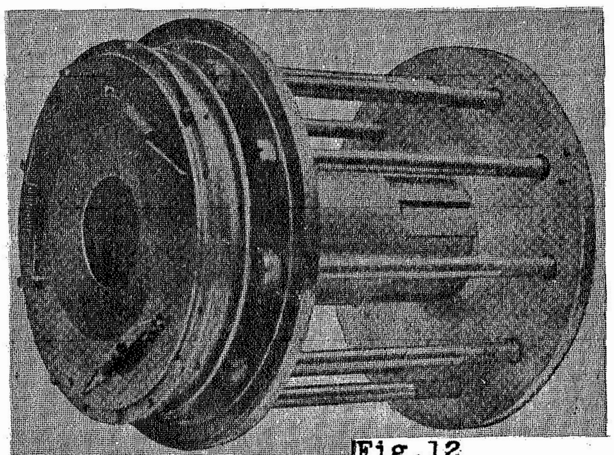

Fig.12 Free-wheel hub assembled.

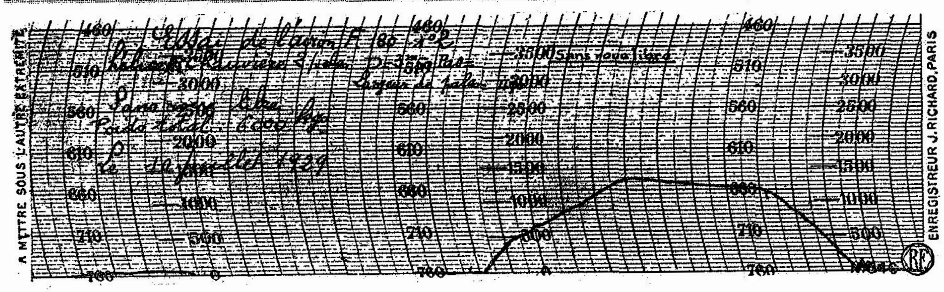

Fig.14 Record of flight with ordinary rear hub. Front engine running at 2100 r.p.m.